Crewed Mars Mission Mode Options for Nuclear Electric/Chemical Hybrid Transportation Systems

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NASA's Human Exploration and Operation Mission Directorate is continuing to study different concepts and options to field human Mars missions as part of NASA's Moon2Mars directive. For crewed missions to Mars, the transportation system sizing is highly dependent on the total mission duration, Mars orbit dwell time, mission concept of operations, and the chosen propulsion system. NASA has been investigating the use of low-thrust electric propulsion systems to augment high-thrust chemical propulsion system for crewed Mars mission to enable a more energy-efficient operations. Recent studies on these missions have focused on "All-Up" piloted mission modes in which the in-space transportation system for crew transit departs Earth with everything it needs for the roundtrip journey, with only the Mars landers and surface assets pre-deployed. This design choice was made to minimize the mission operation risk, as the crew could return safely to Earth in the event of a failure to rendezvous or other failure of any pre-deployed assets. As the Mars Architecture Team continues to investigate and understand the Mars mission trade space, alternate mission mode studies were conducted to understand their impact to the transportation system. These include pre-positioning return assets and discarding expended stages to reduce the overall system mass.

Nomenclature

EOI	Earth Orbit Insertion
LDHEO	Lunar Distant High Earth Orbit
LGA	Lunar Gravity Assist
MDS	Mars Descent System
MOI	Mars Orbit Insertion
NDS	NASA Docking System
NEP	Nuclear Electric Propulsion
SAC21	Strategic Analysis Cycle 2021
SEP	Solar Electric Propulsion
SLS	Space Launch System
TEI	Trans-Earth Injection
TMI	Trans-Mars Injection

I. Introduction

NASA's Mars Architecture Team is continuing the agency's efforts to study and refine the nation's plan to field a sustainable human Mars campaign as part of NASA's Moon2Mars directive. Building upon the success of the

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Design Reference Architecture, Evolvable Mars Campaign, and the Mars Study Capability Team, the group is further developing capabilities to improve the fidelity of the Mars campaign and to continue exploring the design trade space to assess the impact of technology investments and architecture decisions for missions to Mars. Many different mission design concepts have been studied and proposed over the past three decades[1–3]; all of these proposed concepts assumed minimum energy class missions to Mars with roundtrip mission time upwards of three years. This represents a significant leap in the current understanding of the impact on human health for extended exposure to microgravity environment, given the longest continuous crew exposure to microgravity is just over one year. This drives the need for understanding of alternate mission operation modes for human missions to Mars. Previous publication[4] detailed the development of an integrated framework to analyze missions of this nature and showed the performance sensitivity of crewed missions to Mars using a Hybrid Nuclear Electric/Chemical Propulsion system in a "All-Up" piloted mission mode, where the piloted vehicle departs Earth with all of the propellant and supplies needed to perform the roundtrip mission. This design choice was made to minimize the mission operation risk, as the crew could return safely to Earth in the event of a failure to rendezvous or other failure of any pre-deployed assets. The analysis showed significant mass challenges associated with these short duration, high energy roundtrip missions to Mars, especially when the vehicle must carry the roundtrip propellant through the whole journey.

As the Mars Architecture Team continues to investigate and understand the Mars mission trade space, alternate mission mode studies have been conducted to understand their impact to the transportation system. This paper outlines various alternate mission modes for the Nuclear Electric /Chemical Hybrid Propulsion architecture. These alternate mission modes differ from the "All-Up" piloted missions in that they either pre-deploy some of the assets the is required for the return journey, or dispose of stages that have been fully expended during the transit. Pre-deploying assets required for the return journey reduces the burden on the piloted transportation systems significantly, but it requires additional propulsion systems to deliver the return asset. The alternate mission modes were created to understand the impact of changing the risk posture of the transportation system, and seeks to understand the integrated effect of the alternate mission modes on the overall transportation system. This paper documents the mission concepts of operation and provides insight into the potential mass saving each mission modes could provide for different electric propulsion power level and mission duration assumptions. This analysis is a continuing step in understanding the Mars mission trade space for crew missions and will help the agency perform critical design decisions for the Moon2Mars initiative.

II. Hybrid Electric/Chemical Propulsion System

NASA has been investigating and analyzing hybrid electric / chemical propulsion systems to enable human missions to Mars[5–7]. By combining chemical and electric propulsion into a single spacecraft and applying each where it is most effective, the Hybrid architecture enables a series of Mars trajectories that are more fuel efficient than an all chemical propulsion architecture, without significant increases to trip time. Previous efforts focused on minimum energy class missions and utilized Solar Electric Propulsion (SEP) systems[8, 9] as one half of the hybrid propulsion. To enable Mars missions with shorter mission duration, significant increase to the power of the electric propulsion system is needed to keep the overall system mass down. Power level for the solar electric propulsion system was limited to less than 1 mega-watt due to the integration challenges associated with increasingly large solar arrays. An alternate power source for electric thrusters is needed to enable large scale electric propulsion system for shorter Mars missions.

Nuclear Electric Propulsion systems have been studied and proposed in the past for use for planetary exploration missions[10] and cargo delivery for Mars missions[11]. Compared to using solar arrays to power the electric thrusters, nuclear systems have the benefit of constant power provided regardless of solar distance but do come with the cost of a significantly larger system mass and higher system complexity. However, it does come at a cost of significantly heavier system mass and more complex system overall. NASA Glenn Research Center's COMPASS concurrent engineering team developed a concept for a Nuclear Electric / Chemical Hybrid Propulsion[12] system for human Mars missions. The vehicle concept builds upon the design experience from previous nuclear electric propulsion system studies, and implemented updated constraints on the vehicle dimensions and mass. The results is a vehicle concept that has a separate Nuclear Electric propulsion element and chemical propulsion element that are integrated together with the deep space habitation[13] system to support the roundtrip mission to Mars.

A reference Nuclear Electric / Chemical Hybrid Propulsion system has been defined for NASA's Human Exploration Operation and Mission Directorate's Strategic Analysis Cycle 21 (SAC21). The reference propulsion system is depicted in an artist rendering in Figure 1 and expands upon the previous work by the COMPASS team and an internal NASA study on Mars Transportation. The reference propulsion system is similar to the previously published concept[12] but with further refinement. There are four total elements that make up the integrated transportation stack, three

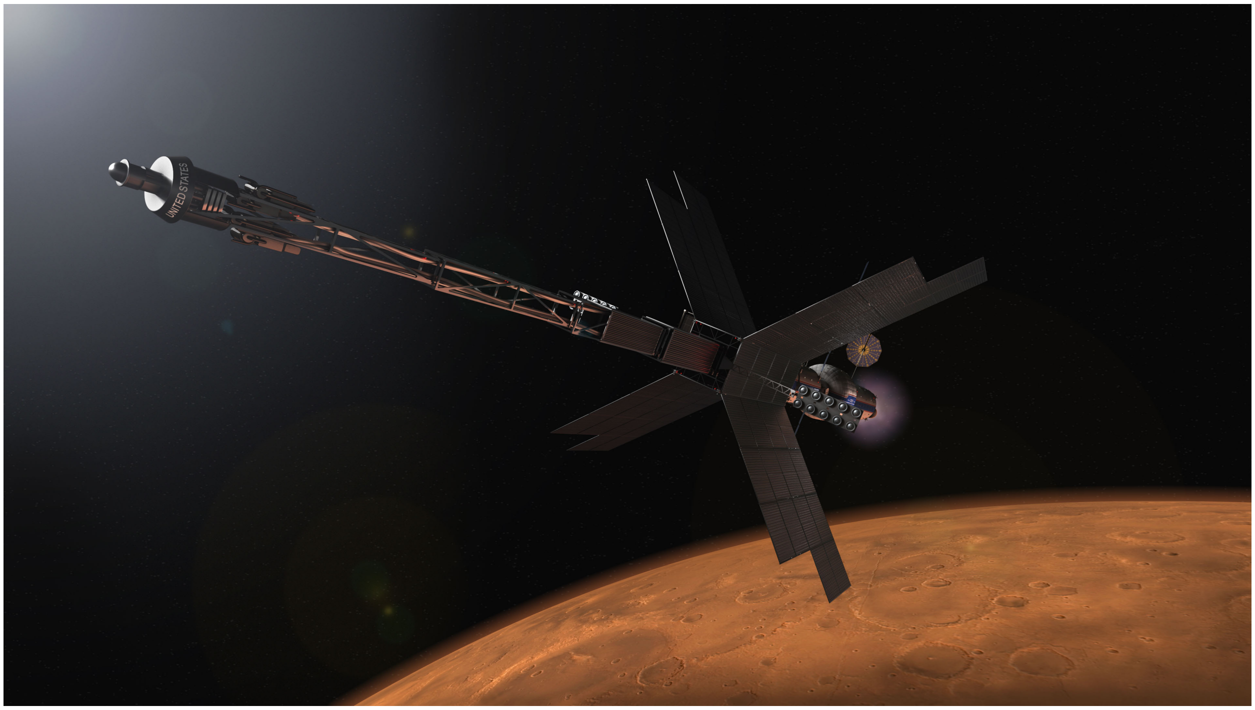

Fig. 1 Concept Rendering of a Nuclear Electric / Chemical Hybrid Propulsion System for Human Mars Exploration Missions

transportation elements and one habitation element. The habitation element assumption remains similar to previous studies and analysis cycles[5, 7, 14] with only minor updates to the habitation system dry mass. For the SAC21 analysis cycle, the habitation system is assumed to have a dry mass of 26,500 kg. The crew logistics and spares required to support the roundtrip mission to Mars is estimated as a function of the overall mission duration, with roughly 21,000 kg of logistics and spare required to support a nominal 760 or 850 days roundtrip mission with a 40 day contingency.

There are three propulsion system elements: the Nuclear Electric Propulsion (NEP) element, the Chemical Propulsion element, and the Xenon Interstage element. The NEP element consists of all of the major element to support the nuclear electric systems, including the nuclear reactor, energy conversion system, heat dissipation radiators, power processing units, electric thrusters, and one of the three xenon tanks that supply the propellant for the integrated vehicle. For SAC21, the NEP system, shown in Figure 2 consists of a 1.8 Megawatt-electric low enriched uranium reactor, with four 500 kilowatt brayton convertors, and $2500m^2$ of deployable radiators to dissipate the waste heat. For the electric propulsion system, the element carries eighteen 100 kilowatt-class hall thrusters[15, 16] on two separate booms with nine thrusters (eight active and one spare) per boom. As seen in Figure 2, the deployable booms provides separation

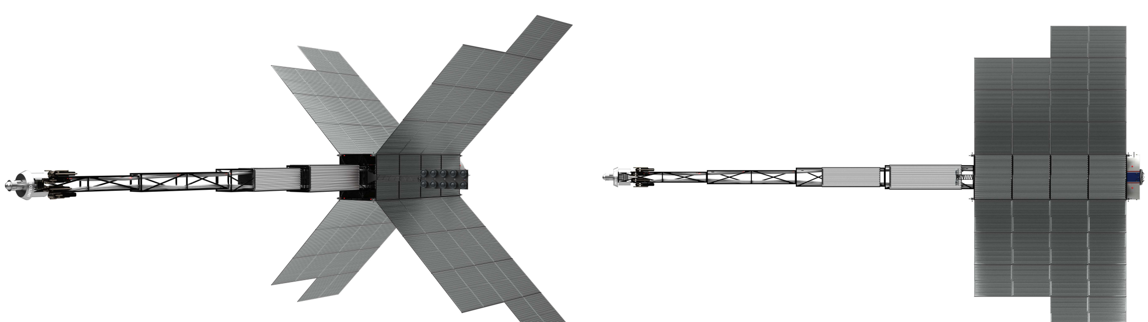

Fig. 2 Concept Rendering of the SAC21 Nuclear Electric Propulsion Element

Fig. 3 Concept Rendering of the SAC21 Xenon Interstage Element

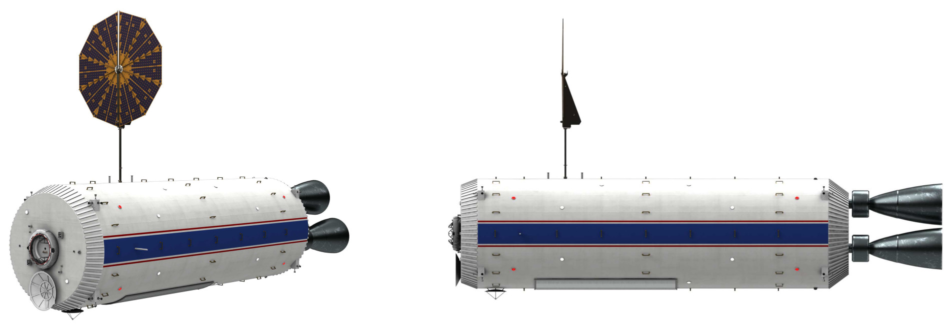

Fig. 4 Concept Rendering of the SAC21 Chemical Propulsion Element

between the reactor, thrusters, and the electronics. The central truss system provides the backbone for the deployable radiator and boom as well as housing the electronics and the xenon tanks within. Finally, deployable solar arrays are utilized for commissioning of the spacecraft and autonomous rendezvous and docking. The element is designed to be launched without xenon propellant on a Space Launch System (SLS) and to utiolize on-orbit refueling of xenon to reach operational capacity.

The Xenon Interstage element's, shown in Figure 3, primary function is to serve as the free flying tanker to hold two of the three xenon tanks for the integrated vehicle, with the third tank embedded inside the NEP element. The Xenon Interstage element is designed to be launched on a commercial launch vehicle with large diameter payload fairing. It houses two 4.5 meter diameter composite over-wrapped pressure vessel storage tanks that can store roughly 42t of xenon each, at ambient 300 kelvin temperature. The element has solar arrays and batteries for commissioning and for autonomous rendezvous and docking operation. It has storable reaction control systems to perform the maneuvers necessary after launch vehicle injections, and houses two NASA Docking System[17] (NDS) to connect the NEP element on one side and the habitation system on the other. The element is designed to be launched partially fueled with xenon in its tanks, with additional propellant resupplied in orbit to reach operational capacity.

The Chemical Propulsion element, shown in Figure 4, is a liquid oxygen/liquid methane chemical propulsion system similar to existing launch vehicle upper stages. It has internal common bulkhead propellant tanks that can carry up to 200t of propellant, with appropriate insulation and cryocoolers to keep the two propellants at cryogenic temperatures. It has solar arrays and batteries for commissioning and for autonomous rendezvous and docking operations. It utilizes storable reaction control systems to perform post launch injection maneuvers. For the main propulsion system, the element utilizes three RL-10 class chemical engines that have been converted to use oxygen and methane as its propellant. It houses two NDS, one active NDS for connection to the habitation system (or other cargo if the system is

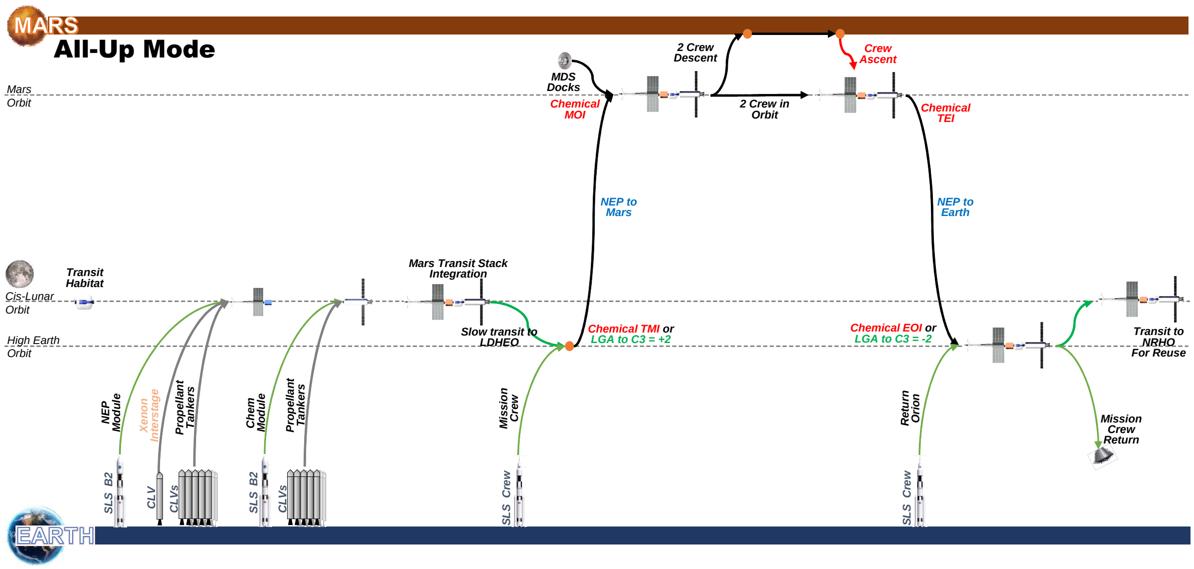

Fig. 5 "All-Up" Mission Mode Concept of Operation for a Crewed Mission to Mars using Nuclear Electric / Chemical Hybrid Propulsion System

utilized for cargo delivery) and one passive NDS for on-orbit refueling. The element is designed to be launched mostly empty on a SLS with propellant resupply in orbit.

For the integrated mission analysis in this study, a parametric model of the three propulsion system element was created using a detailed bottoms-up, model as anchor points. The detailed model of the propulsion system was created with assistance from the GRC COMPASS team using the LaRC EXAMINE[18] modeling framework. The parametric model that was created for this study allows for sizing of each of the system based primarily on the propellant demand from the trajectory optimization, which will be discuses in detail in the following section. Due to the nature of the low thrust trajectory optimization, the mass sizing of the element and trajectory optimization has circular dependency relationship and must be solved concurrently.

III. Definition of Mission Mode Options

All of the mission modes options considered in this study have several common assumptions with regards to their concepts of operation. The individual elements are launched on separate launch vehicles to high Earth orbit, then boosted to cis-lunar space for aggregation into the integrated Mars transit vehicle. Propellant resupply operation also occurs in cis-lunar space, as the elements are launched mostly empty. The habitation module is also outfitted in cis-lunar space with the necessary logistics and spares for the crewed mission to Mars in cis-lunar space. Once the integrated vehicle has been fully provisioned, the vehicle performs a low energy transit into a lunar distant high Earth orbit (LDHEO) that's roughly 400 x 400,000 km in altitude. The mission crew then launches on an Orion vehicle to meet the transport in LDHEO, where final checkout of the integrated vehicle is performed by the crew prior to the Earth departure maneuver. Similar to previous mission concepts[5], the vehicle has the options to perform a low energy lunar gravity assist (LGA) maneuver as part of its Earth departure or Trans-Mars Injection (TMI) maneuver, if the trajectory offers an opportunity to do so. Performing this maneuver increases the mission duration by 30 days due to phasing and targeting requirement of the LGA maneuver. After Earth departure, the nuclear electric propulsion system is utilized during the transit to continuously thrust to increase the vehicle's energy to target a Mars rendezvous. A chemical Mars Orbit Insertion (MOI) burn is performed to capture into Mars 5-sol parking orbit, where the pre-deployed Mars Descent System (MDS) will rendezvous with the transport to carry the crew to the surface of Mars. For this study, a nominal surface mission of 30 days is assumed. The Mars transport spends a minimum of 50 days in Mars orbit to account for the 30 days of Mars surface mission and the necessary time required for rendezvous between the lander, ascent stage, and the transport, and the time required for the crew to transit to and from the surface. After the crew returns to the transport from the surface, the vehicle performs chemical Trans-Earth Injection (TEI) maneuver to depart

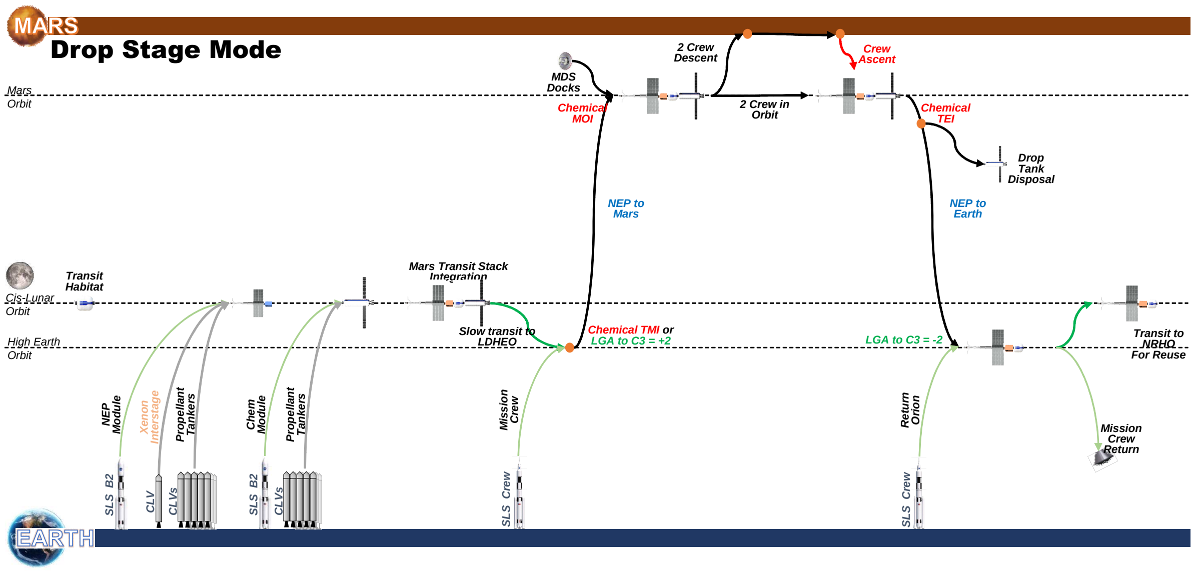

Fig. 6 "Drop Stage" Mission Mode Concept of Operation for a Crewed Mission to Mars using Nuclear Electric / Chemical Hybrid Propulsion System

Mars, uses the NEP system during the transit home, and finally arrives at Earth using either a direct chemical Earth Orbit Insertion (EOI) maneuvers or a combination of chemical and LGA maneuver. A second Orion is launched to rendezvous with the transport in the LDHEO to return the crew to Earth surface, while the transport returns to cis-lunar space for potential reuse. These operations are similar across the different mission modes, the difference between the modes comes from additional operations required to enable the roundtrip missions.

Figure 5 shows the "All-Up" mission mode of operation. The "All-Up" in this context refers to the piloted portion of the mission, in which the crew and the crew transportation vehicle departs Earth with all of the propellant and supplies it needs to complete the roundtrip mission. This represents the lowest risk posture from the mission mode perspective, as it does not require rendezvous and docking of any assets for the crew to return safely back to Earth. The nominal mission requires the rendezvous and docking with a pre-deployed MDS to facilitate the Mars surface operation, however, in the event of a surface mission abort, there are no additional rendezvous and docking maneuvers required at Mars for the crew to return home.

Figure 6 shows the "Drop Stage" mission mode of operation. For this mission mode, the crew still departs Earth with all of the propellant and supplies needed to perform the roundtrip mission to Mars. The operation is the same through the Mars surface stay, but after the completion of the TEI maneuver, the Chemical Module is jettisoned and discarded. This reduces the dry mass of the overall vehicle stack, which increases the efficacy of the low-thrust NEP system during the transit back to Earth. Without the chemical module, the vehicle will be unable to perform high thrust Earth capture maneuver, thus the vehicle must rely on targeting a LGA maneuver to capture the vehicle into the LDHEO to rendezvous with the second Orion vehicle for crew return to surface. This puts additional constraints on the NEP system to target specific Earth arrival conditions to enable this maneuver. Additionally, the mission duration is slightly increased as the LGA maneuver typically adds 30 days to the mission time line.

Figure 7 shows the "Pre-Deploy" mission mode of operation. This mission mode represents a significant departure from the standard risk posture associated with the previous two mission modes. For this mission mode, the crew and the crew vehicle departs Earth with only enough propellant for the one-way trip from Earth to Mars. In order for the crew to return home to Earth, they must rendezvous and dock with a pre-deployed chemical and/or xenon stage in Mars orbit to take on additional propellant for the return journey. Several options exists for this mission mode. The pre-deployed assets could be a series of propellant tankers that refuels the piloted vehicle in Mars orbit. This option presents a few challenges. First, even though the transportation vehicle is designed to be refueled in space, refueling operations are typically performed autonomously without crew on-board the vehicle. It's unclear if performing refueling operation poses any additional risks to the crew. Second, during the initial refueling concept of operation in cis-lunar space, the vehicle's configuration is different from the flight configuration, and additional studies are required to understand

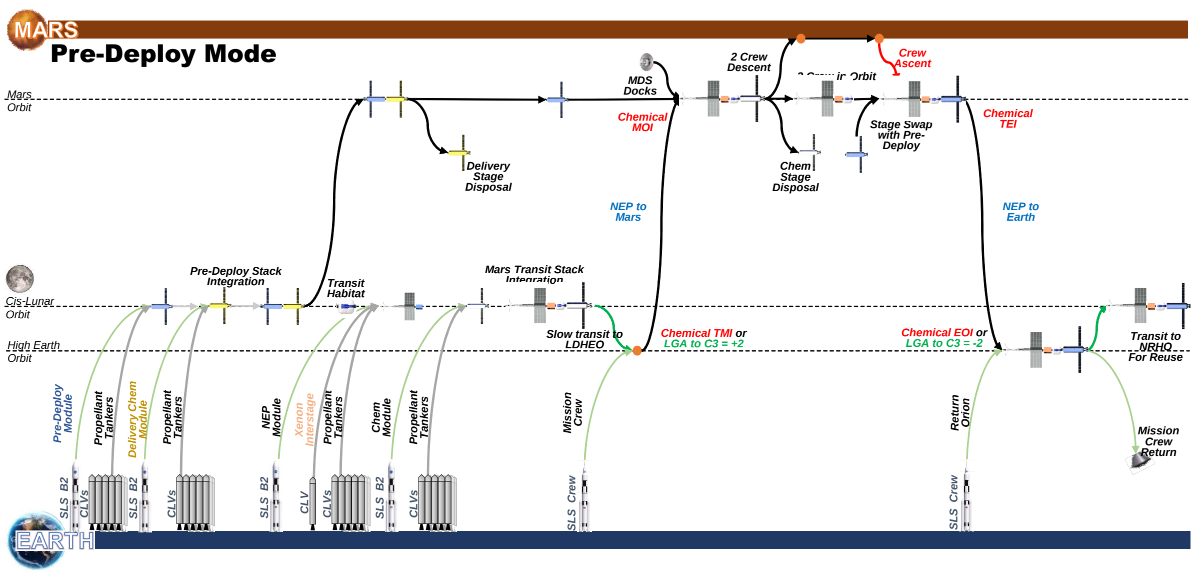

Fig. 7 "Pre-Deploy" Mission Mode Concept of Operation for a Crewed Mission to Mars using Nuclear Electric / Chemical Hybrid Propulsion System

the impact to the vehicle design if refueling operations are needed while the vehicle is in its final flight configuration. Finally, the current study assumption has a nominal surface mission of 30 days with a 50 sols in Mars orbit, in which all of the rendezvous, docking, and refueling operation must be performed. Additional studies are required to understand the time required to perform these operation. A slightly more simplistic option to enable the "pre-deploy" mission mode is to perform a stage swap. For this option, the pre-deployed asset would be an additional fully fueled chemical module and/or xenon interstage module, and the piloted vehicle would simply exchange the spent stages for fueled modules. This still requires rendezvous and docking of additional elements, and potential configuration management of the element in Mars orbit, but it removes the propellant transfer in Mars orbit. For this study, the stage swap method was selected as study reference, as shown in Figure 7.

The second portion of this mission mode that must be considered is the delivery of the pre-deployed asset. Several options exists for this phase of the mission mode as well. The primary benefit of the pre-deploy mission mode is that even if the piloted vehicle is performing higher energy short duration Mars mission, the pre-deployed asset could leverage minimum energy transfer to Mars to reduce the overall propellant and launch mass required. Of course, the efficiency of the delivery vehicle would be the primary driver of this potential saving. For a mass optimal solution, the higher the efficiency of the delivery vehicle, the better the pre-deploy mission mode becomes. Thus it's natural to assume a NEP based delivery system would be most efficient. However, utilizing the NEP system to deliver the pre-deploy stage poses significant challenge to the mission campaign cadence, as it moves the first need date of the nuclear element significantly earlier than the non pre-deploy mission modes. For this reason, this study assumes the utilization of the chemical module to deliver the pre-deploy assets to Mars on a minimum energy trajectory.

The final mission mode for this study, shown in Figure 8, combines the "Drop Stage" and the "Pre-Deploy" mission mode of operation. For this mission mode, the crew departs Earth with all of the xenon propellant required for the roundtrip mission but only enough chemical propellant for the outbound portion of the journey. In Mars orbit, the fully expended chemical module is swapped out for a pre-deployed chemical module, and this module is utilized only for the Mars departure TEI maneuver, as it is jettisoned immediately after the maneuver. This provide the benefit of reducing the dry mass of the overall transportation stack for the return journey and reducing the propellant required on the outbound portion by not carrying a portion of the return propellant. The piloted vehicle will return to Earth without the chemical module, thus requiring LGA maneuver and the additional mission duration associated with it.

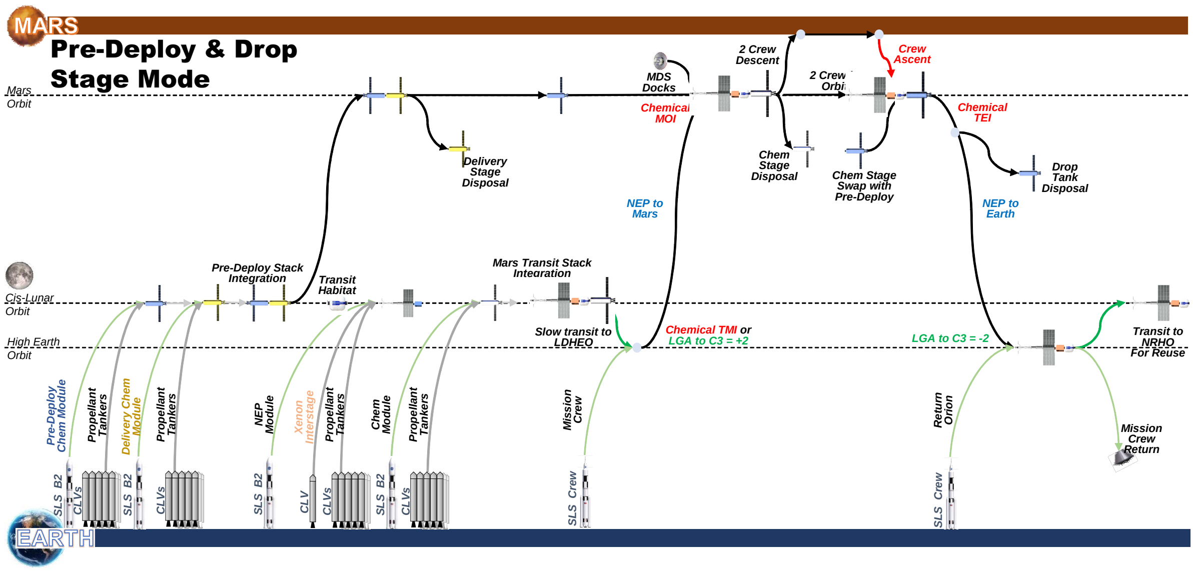

Fig. 8 "Pre-Deploy + Drop Stage" Mission Mode Concept of Operation for a Crewed Mission to Mars using Nuclear Electric / Chemical Hybrid Propulsion System

IV. Mission Mode Performance Comparison

To provide performance comparison between each of the mission modes considered in this study, the total roundtrip mass required at Earth departure was selected as the primary metric. The mass includes the total piloted vehicle stack, plus the pre-deployed propellant and system, as well as the delivery propellant and system. This provides an overall assessment of the end-to-end propulsion system requirement for the piloted mission and direct comparison between the different mission modes from a purely performance perspective. Additional analysis outside the scope of this study will be required to understand the impact to other metric of interest, such as cost, schedule, and risks.

Figure 9 shows the Earth departure mass comparison between five different mission modes: All-Up, Drop Chemical Stage, Pre-Deploy Chemical Stage, Pre-Deploy plus Drop Chemical Stage, and Pre-Deploy both Xenon and Chemical Stages. The solid color bars shows the mass of the integrated piloted vehicle at Earth departure, while the patterned bars show the pre-deploy and delivery propellant and systems. This figure shows performance of a nominal mission of 760 days interplanetary roundtrip duration, that is from the TMI maneuver to the EOI maneuver. The 760 day duration does not include the additional time required to perform phasing, rendezvous, and docking maneuvers in Earth orbit to get the crew into and out of the Orion, so the total crew time in space will be longer than 760 days. Looking at only the solid color bars, it's clear that the "All-Up" mission mode is represent the most challenging mission mode of operation. This isn't surprising as the transportation system has to push the full roundtrip mission propellant and dry mass through every maneuver, and the exponential nature of the rocket equation makes this a significant challenge. Significant mass saving can be achieved by simply dropping the chemical stage after the TEI maneuver, as the system sheds a significant portion of its inert mass, which significantly improves the performance of the NEP system and reduces the overall propellant required. Additional mass saving can be achieved with pre-deploying chemical and xenon stages at Mars, even when accounting for the additional mass required to deliver the pre-deployed elements.

These results shows the significant challenge associated with the high energy 760 day roundtrip mission to Mars. As discussed in previous paper[4], the short 700-760 day interplanetary duration missions sits on the exponential part of the sensitivity curve for the study reference NEP/Chemical Hybrid propulsion system, thus these changes to the mission modes have significant mass impact to the overall system as compared to the baseline "All-Up" mission mode. One option to reduce the sensitivity is to increase the power to the NEP system, however, increasing power to the NEP system would likely require additional inert mass to the transportation system and poses potential additional development risk to the campaign. Additionally, the NEP system as currently designed in the study reference is fully utilizing the payload fairing of the launch vehicle. Adding more power to the system will likely require redesign and repackaging of the NEP system into multiple launch vehicles and would require in-space assembly of complex fluid and electric loops.

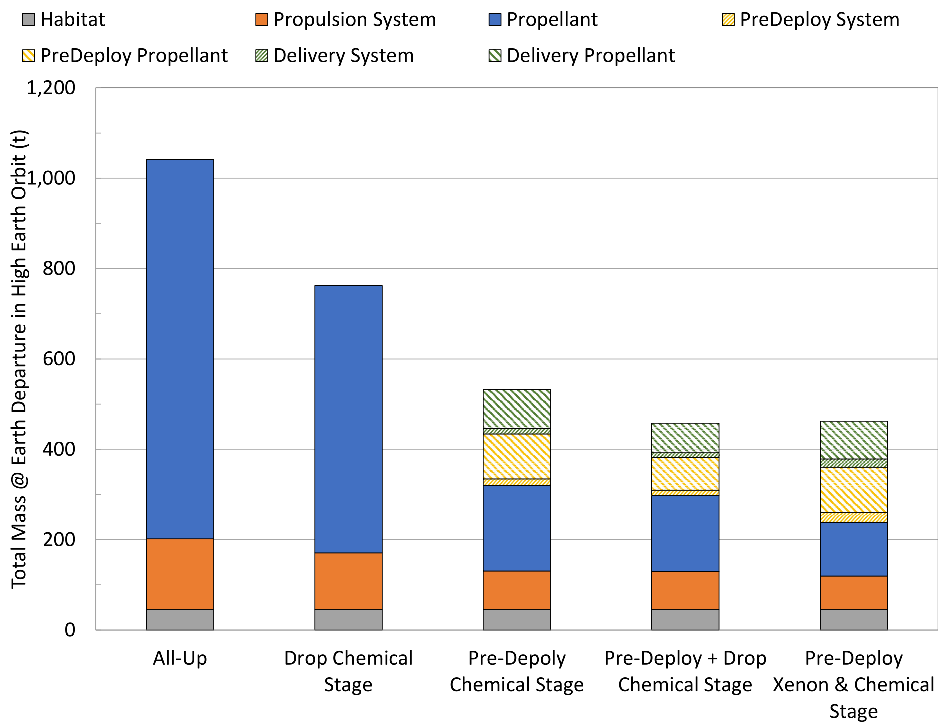

Fig. 9 Earth Departure Mass Comparison between Piloted Mission Mode for a 760 Days Interplanetary Duration Roundtrip Mission to Mars with 50 Days in Mars Orbit

The alternate mission modes shows significant mass reduction compared to the "All-Up" mission mode. However, each mission mode represent added risk to the overall architecture that's not captured in the mass saving. As previously discussed, the "All-Up" mode represent the lowest risk posture from the piloted mission perspective, as the crew can complete the roundtrip mission to Mars without interacting with any additional element. Any alteration to this mission mode represents a departure from this risk posture. The "Drop Stage" mission mode requires the jettison of the chemical stage immediately after it completes a major maneuver and before the NEP system begins its thrusting maneuver. Comparatively, this mission mode does not add significant risk to the overall architecture, however, a failure to jettison the stage will result in a loss of crew and loss of mission as the NEP system does not have enough propellant to push the empty chemical stage back to Earth. The "Pre-Deploy" mission mode adds significant risk to the architecture, as any failure in the pre-deploy system or in the rendezvous and docking maneuvers in Mars orbit will result in loss of crew and loss of mission. These risks must be balanced with the potential mass saving that is shown in Figure 9. Additional metric such as launch and development schedule of the elements as well as cost of the campaign must also be considered.

An alternate comparison for the mission modes is shown in Figure 10, which shows the same comparison of the Earth departure mass for the give mission modes, but for a 850 days interplanetary roundtrip mission to Mars. The 850 day mission represents a significantly easier mission for the study reference NEP/Chemical Hybrid transportation system to perform, as evident by the significant reduction in the overall mass required compared to the 760 day mission. For this mission, the mass variation across the five mission modes are not nearly as dramatic. In fact, for the 850 days mission, the "All-Up" mission mode is one of the lowest mass solution while also being the lowest risk solution. This shows the extreme sensitivity of the overall mission performance to duration as previously discussed[4]. For the 850 days mission, with all of the risk discussion on the 760 days comparison, there is no compelling reason to perform any of the alternate mission modes.

V. Summary

In this paper, an analysis of potential alternate mission modes for the Nuclear Electric / Chemical Hybrid Propulsion system for roundtrip missions to Mars was presented. Five different mission modes were compared from an Earth

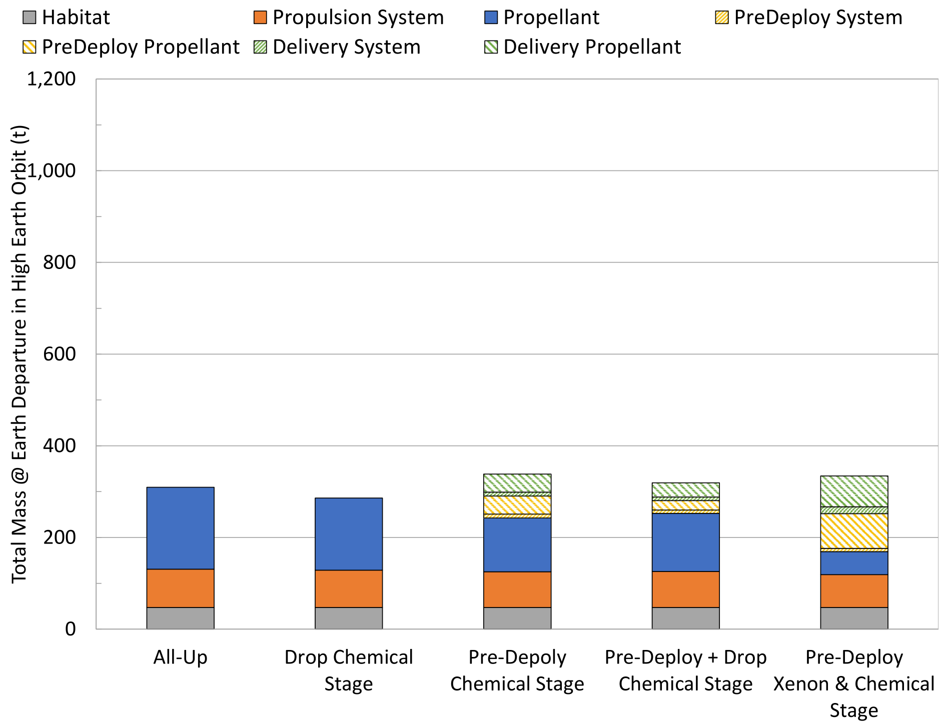

Fig. 10 Earth Departure Mass Comparison between Piloted Mission Mode for a 850 Days Interplanetary Duration Roundtrip Mission to Mars with 50 Days in Mars Orbit

departure mass standpoint to evaluate the top level performance characteristics of each. These alternate mission modes were compared to the reference "All-Up" mission mode, in which the piloted vehicle departed Earth with all of the propellant and logistics required to support the crew's roundtrip mission to Mars. The "Drop Stage" mission mode represented a small step up in the risk posture, requiring only the jettison of the expended chemical module after the Mars departure maneuver, while providing tangible mass saving compared to the reference mode. Pre-deploying return assets at Mars represented a major step up in the risk posture, requiring the crew the rendezvous, dock, and swap out expended modules for fully fueled modules in Mars orbit in order to be able to return to Earth. However, this mission mode resulted in significant mass saving compared to the reference mission mode, which must be balanced with the added risk. Mission duration remained the most significant driver to the mission mass, as shown in previous studies[4]. Modest increase to the mission duration eliminated the potential mass savings from alternate mission modes, which negates the benefits gained from the added risks of these alternate mission modes. A balanced analysis between the mission performance, risk, scheduled, and cost will be needed to understand the full impact of these alternate mission modes and evaluate their fitness compared to the reference mission mode.

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